Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 93 (2016) 96 – 101

Energy Procedia

Africa-EU Renewable Energy Research and Innovation Symposium, RERIS 2016, 8-10 March 2016, Tlemcen, Algeria

Techno-economic assessment of solar hydrogen production using CPV-electrolysis systems

Rafika Boudries[a]*

[a]*Centre de Développement des Energies Renouvelables, Route de l'Observatoire, Bouzareah, 16340, Algiers, Algeria*

Abstract

Interest in developing hydrogen production technologies stems from the need to develop another source of energy that is sustainable and environmentally friendly. This interest results also from the growth in energy needs for hydrogen as a feedstock. Water electrolysis is the sustainable and clean hydrogen production process that has reached the industrial maturity.

In the present work, a techno-economic assessment of hydrogen production using an electrolyser- concentrating photovoltaic (CPV) system in Algeria is carried out. Different technologies of solar concentration and of photovoltaic modules are considered. The dependence of hydrogen production potential and of hydrogen production cost on these technologies is investigated. By comparison to common PV-electrolysis method, the CPV-electrolysis technique offers a much higher production rate at much more competitive cost.

© 2016 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of RERIS 2016

Keywords: Hydrogen production potential, hydrogen production cost, CPV, solar concentration, water electrolysis.

* Corresponding author. Tel.: +0 213 23 18 90 51; fax: +0 213 18 90 56.
E-mail address: r_zaka@yahoo.fr

1876-6102 © 2016 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the organizing committee of RERIS 2016
doi:10.1016/j.egypro.2016.07.155

1. Introduction

There is a worldwide consensus that alternative sources of energy must be developed. This stems from concerns about the conventional energy sources capacity of meeting world energy needs and about the adverse effects on the environment resulting from their use. Strong argumentations have been advanced in favour of hydrogen as an energy vector [1]. Indeed, hydrogen could be used as a clean and sustainable source of energy, resolving then the environmental and availability problems resulting from the conventional energy sources. In addition, hydrogen can alleviate the intrinsic problems of renewable energy systems, such as intermittence, site specificity and mismatch between energy demand and supply. As an energy vector, hydrogen exhibits the sustainability and the environmental friendliness attributes of renewable energy. It exhibits also the high mass energy density and capability of long term storage and long distance transport attributes of conventional energy [2].

Energy from hydrogen can be used in different fields, ranging from the transport and the power-utility sectors to household applications. At the national and international levels, scenarios are proposed and major programs are undertaken for hydrogen energy development and implementation [3]. However, a prerequisite for the market penetration of hydrogen as an energy vector is its availability at a competitive price.

Nonetheless, hydrogen is available in nature mainly in combination with other elements and must then be produced. To this end, there are various production processes. Each process requires a feedstock from which the hydrogen is extracted and a source of energy to enable this extraction. Feedstock could be any raw substance containing hydrogen such as water or hydrocarbon. The energy could be of conventional, renewable or nuclear origin[4]. Some of these techniques, such as steam reforming and water electrolysis, have reached the commercial maturity stage; while others are still at the experimental stage. Hydrogen production using solar energy based techniques is currently object of intense investigation [1]. Indeed, thanks to its availability and its renewable and pollution-free character, solar hydrogen is considered as one of the alternatives which contribute to tackle the energy problem. Among these techniques, the concentrating photovoltaic technology deserves special attention.

In the present work, a techno-economic analysis of hydrogen production using processes driven by solar energy is carried out. For the solar-based hydrogen production, a CPV-electrolyser system is considered. First, the techniques of hydrogen production are discussed. Emphasis is put on the use of renewable feedstock. Then, the CPV systems are briefly reviewed and their capacity of producing both clean and renewable electrical and thermal energy is highlighted. The technique of water electrolysis is briefly discussed, and the importance of using heat to increase the system energy efficiency and its economic viability is shown. Finally, a techno-economic assessment of the production potential and of the production cost of hydrogen using a CPV-water electrolyser system is carried out. Moreover, the effect of different parameters, such as the concentration ratio, the efficiency of the solar cells, the temperature and the capital costs, on the viability of hydrogen has been investigated.

2. Methods

2.1. Methods of techno-economic assessment of hydrogen production

In the present work, an electrolyser unit coupled to a concentrator photovoltaic unit is considered. This system offers not only the generation of direct current (DC) power that is well suited for the electrolysis unit, but also flexibility and modularity. This system enhances also the production of hydrogen. Indeed, on one side, concentration increases the incident solar irradiance leading to a higher electrical energy generation and on the other side, heat generation leads to a reduction in electricity requirement for electrolysis [5]. Besides these units, the system includes the auxiliary units such as the control and regulation unit, the tracking system, the water supply and treatment unit, the heat exchanger unit and the produced gas separation unit.

In the following, an assessment of the potential and of the cost of hydrogen production using this technique is carried out.

2.2. Potential of hydrogen production

Concentrating photovoltaic unit: The CPV unit, needed for the generation of electricity and heat, is mainly made of parabolic trough reflectors for solar concentration and water cooled PV cells placed at the focal line of the parabolic trough. The system is equipped with a two-axis tracking system. The electrical energy generated is given by [5]:

$$E_{elec} = \eta_{op}\eta_{\mathrm{mod}}\eta_{cell}(K_{IAM}\,CH_b + H_d) \tag{1}$$

Where H_b and H_d are respectively the beam radiation and the diffuse radiation incident on the reflector, C the concentration ratio, η_{op} is the optical efficiency, η_{cell} the cell efficiency and K_{IAM} is the electrical solar incident angle θ modifier which is given by the relation:

$$K_{IAM} = 1 - b_{oe}\left(\frac{1}{\cos\theta} - 1\right) \tag{2}$$

b_{oe} is a constant. It is reported to be equal to 0.003/°C [6].

Electrolysis unit: The electrolysis unit main component is the electrolyser cells rack. The energy required for water electrolysis, at temperature T, is theoretically given by the change in the enthalpy of reaction ΔH which is expressed by:

$$\Delta H = \Delta G + T\Delta S \tag{3}$$

ΔG is the change in Gibbs free energy and ΔS the change in entropy. The electrical energy required for water electrolysis is related to ΔG while the thermal energy to T ΔS. The thermal energy fraction required for electrolysis is thermodynamically determined. It depends on the temperature and the ratio of TΔS to ΔG. Details on the determination of ΔH and ΔS for the different elements entering in the electrolysis process have already been reported [7]. The hydrogen production potential *n* is given by [8]:

$$n = \frac{E_T}{\Delta H}\eta_{el} \tag{4}$$

Where η_{el} is the electrolyser efficiency, ΔH is the enthalpy of reaction and E_T is the total energy used for water electrolysis. Electrolysis water temperature is assumed to 100 °C. The pressure is taken to be 5 bars.

Solar radiation: Besides the performance characteristics of its components, the assessment of the system production capacity requires also knowledge of the level and distribution of solar radiation as well as the meteorological data such as wind speed and temperature. To this end, standard methods [9] are used.

2.3. Cost of hydrogen production

The cost of hydrogen production could be divided into the cost of electricity production and the cost of electrolysis. The electricity production cost is relative to the cost of the concentrating photovoltaic unit and the related operation and maintenance costs. The cost of electrolysis is relative to the cost of the electrolysis unit and the related operation and maintenance costs. Previous studies have shown that the capital costs depend on the size of the hydrogen production unit and on the technology maturity [10].

Electricity related cost: For the electricity cost, the cell capital cost C_{cel}, the PV capital cost C_{mod}, the balance of system (BOS) cost C_{BOS}, the tracking system cost C_{tr} and the operational and maintenance costs and related costs

C_{OM} must be taken into account. Moreover, the capital cost C_{BP} of the power related to the balance of system has to be added. The electricity production cost is then estimated using the following relation [11]:

$$C_e = \frac{K(C_{BOS} + C_{tr} + C_{\mathrm{mod}} + C_{el}/C + C_{BP}\ I_p\ \eta_{op}\ \eta_{\mathrm{mod}}\ \eta_{BOS})}{31.536 H_{\mathrm{mod}}\ \eta_{\mathrm{mod}}\ \eta_e\ \eta_{op}\ \eta_T} \tag{5}$$

The optical efficiency η_{op} , the module efficiency η_{mod} and the BOS efficiency η_{BOS} are taken to be 0.90, 0.12 and 0.85, respectively. I_p is equal to 1 kW/m^2 and H_{mod} is the irradiance incident on the PV module.

The value of the economic factor K has been estimated to be 0.096.

Electrolysis related cost: There are different models for the electrolysis cost assessment [12]. In the present work, this cost is evaluated using the following relation:

$$C_{elec} = \frac{K_{el}}{31.536 n_r CF} C_{em} \left[f_1 + (1 - f_1)\frac{i_r}{i} + \frac{f_2}{2}(1 + \frac{i_r}{i}) \right] \tag{6}$$

with C_{em} being the electrolyser capital cost, i and i_r the operating and rated current respectively, CF the electrolyser capacity factor and K_{el} the economic factor. The parameters f_1 and f_2 are constants that depend on the electrolyser technology. Values of these parameters are reported elsewhere [13].

3. Results and discussion

Figure 1 shows the hydrogen production rate for different sites in Algeria. Earlier work has been carried out on hydrogen production using a regular flat PV-electrolysis system [3]. Comparing the results obtained in this earlier work and the present work, it can be seen that the hydrogen production rate using the concentrating photovoltaic system is much higher than that of using regular flat photovoltaic [3]. This is expected as the concentrating photovoltaic system allows collection of much higher solar radiation intensity and possibly thermal energyas a result of concentration. The collection of higher solar radiation intensity leads to a higher production of electrical energy and the use of thermal energy in water electrolysis reduces the need for electrical energy in hydrogen production.

It can also be noticed that hydrogen production varies significantly over the months with the site region. For July, it is though practically the same for all the sites under consideration. This is not the case for the other months of the year where it is clearly much lower in the North.

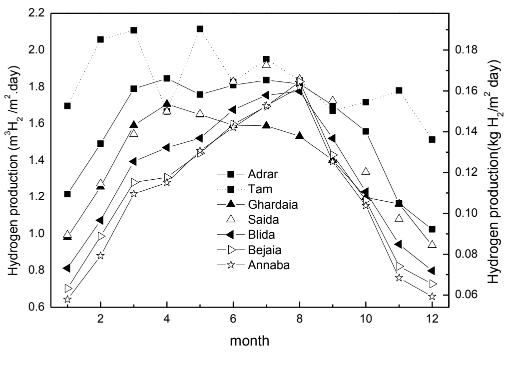

Fig. 1. Evolution of the mean daily hydrogen production rate in different months.

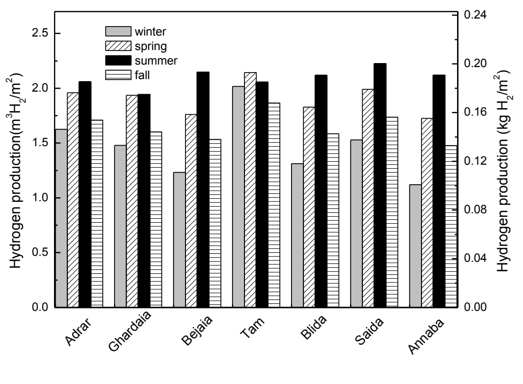

Fig. 2. Seasonal evolution of the monthly mean of hydrogen production rate.

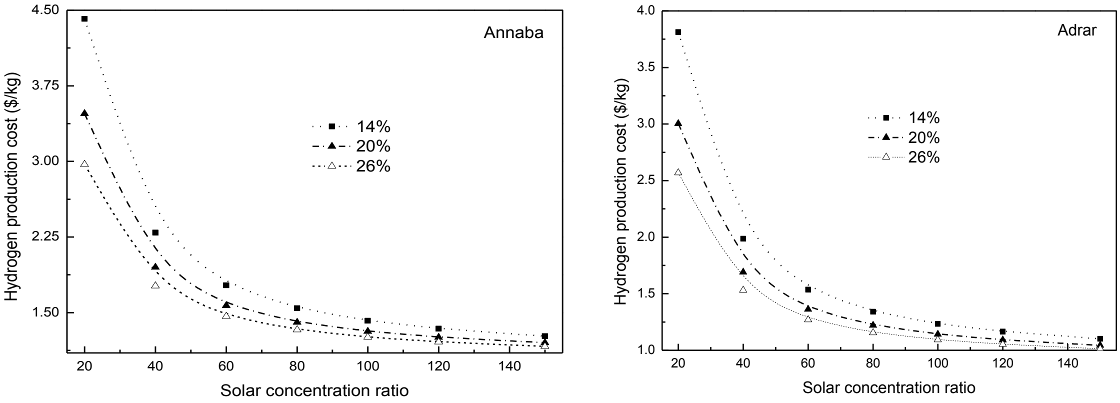

Fig. 3. Hydrogen production cost variation with solar concentration for different values of cell efficiency.

The seasonal evolution of the hydrogen production rate is also investigated. Figure 2 shows that the production rate, for a given site, is not uniform through the seasons. For inter-regional hydrogen production rates, it can be noticed that t here are important differences in the hydrogen production between the different sites. This is particularly true for the winter season.

The variation of the production cost of hydrogendependence of the solar concentration ratio for different values of cell efficiency is reported in Figure 3. From this figure, a fast drop in hydrogen cost with an increase in concentration ratio can be noticed. However, this drop in cost levels off. At high concentration ratios, concentration and even cell efficiency do not affect much this cost.

In Figure 4, the concentrating photovoltaic fractional cost and the electrolysis fractional cost are reported. The concentrating photovoltaic fractional cost is the ratio of the concentrating photovoltaic unit related cost to the total cost of hydrogen production. It represents the fraction of the cost of hydrogen related to the concentrating photovoltaic unit. The same, the electrolysis fractional cost is the ratio of the electrolysis unit related cost to the total cost of hydrogen production. It represents the fraction of the cost of hydrogen related to the electrolysis unit.

From this figure, it can be seen that at low concentration, the cost of hydrogen production is dominated by the concentrating photovoltaic unit-elated cost. It can though be noticed that this fractional cost drops as the efficiency and the solar irradiation increase. However, as the solar concentration increases, the CPV-related cost drops rapidly. The hydrogen cost is dominated by electrolysis unit-related cost.

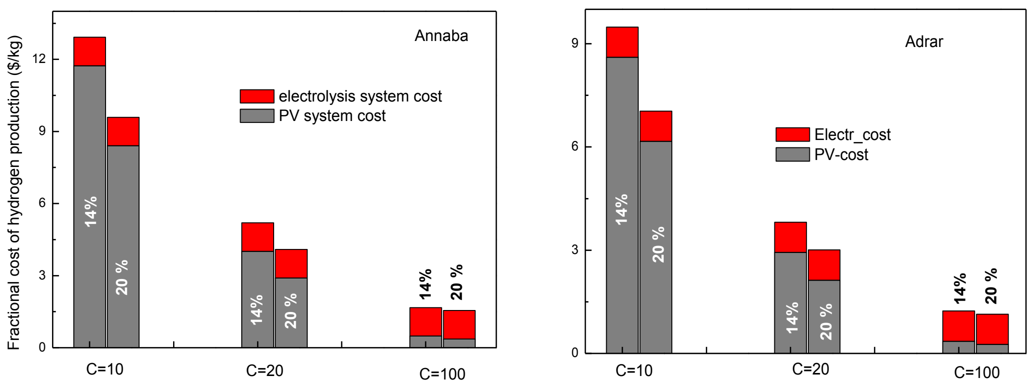

Fig. 4. Estimation of the hydrogen production fractional cost variation with solar concentration for different values of cell efficiency. C is the solar concentration ratio.

4. Conclusions

Hydrogen production using the CPV-electrolyser system technique allows the production of high purity hydrogen necessary for operating fuel cells and other energy and non-energy-related applications. These results indicate that CPV technology could be used to produce hydrogen in an efficient and economical way. Indeed, using reflectors reduces the needed solar cells surface leading to a decrease in electricity production cost. Solar concentration leads also to higher energy intensity resulting in an increase in the specific electrical energy generation coefficient. Production rate increases with increase in solar concentration ratio and in electrolysis temperature. The hydrogen production rate cost, on the other hand, decreases with increasing solar concentration ratio.

Experimental study of the production of hydrogen using a concentrating photovoltaic – electrolysis system is under consideration. The effects of different parameters, such as the meteorological conditions and the concentrating photovoltaic technology, on the performance of the concentrating photovoltaic – electrolysis system is to be investigated. This could be carried out in the framework of the partnership between African and European institutions.

References

[1] Boudries R, Dizene R, Khellaf A, Belhamel M. Hydrogen as an energy carrier. In: Harris Aiden M, editor. Clean energy: resources, production and developments. New York : Nova Science Pub., Inc., 2010 p. 147-184.

[2] Duu-Hwa Lee, Ching-Pin Hung. Toward a clean energy economy: With discussion on role of hydrogen sectors. Int J Hydrogen Energy 2012; 37:15753-15765.

[3] Boudries R, Dizene R. Potentialities of hydrogen production in Algeria. Int J Hydrogen Energy 2008; 33:4476-4487.

[4] Rajishwar K, Mc Connell R, Licht S. Solar hydrogen generation: toward a renewable energy future, New York: Springer-Verlag; 2008.

[5] Boudries R. Analysis of solar hydrogen production in Algeria: Case of an electrolyzer-concentrating photovoltaic system, Int J Hydrogen Energy 2013; 38:11507-11518.

[6] Bernardo LR, Perers B, Hakansson H, Karlsson B. Performance evaluation of low concentrating photovoltaic/ thermal systems: a case study from Sweden. Sol Energy 2011; 85:1499-510.

[7] Moran MJ, Shapiro HN, Fundamentals of engineering thermodynamics. 5th ed. New York: John Wiley Inc; 2004.

[8] Padin J, Veziroglu TN, Shahin A. Hybrid solar high-temperature hydrogen production system. , Int J Hydrogen Energy 2000; 25: 295-317.

[9] Duffie JA, Beckman WA, Solar engineering of thermal processes. 3rd ed. New York: Wiley, Inc; 2006.

[10] Harmon C. Experience Curves of Photovoltaic Technology. Interim Report IR-00-014. International Institute for Applied Analysis, Laxenburg, Austria. 2000.

[11] Boudries R. Comparative economic competitiveness assessment of hydrogen as a fuel in the transport sector in Algeria. Chem Eng Trans 2014; 42: 61-66.

[12] Boudries R, Dizene R. Analysis of solar hydrogen production potential in Algeria: case of an electrolyser-PV tracking system. In Mendez-Vilas A editor. Fuelling the Future: Advances in Science and Technologies for Energy Generation, Transmission and Storage. Boca Raton: Brown Walker Press; 2012. p. 307.

[13] Ogden Joan M. Renewable hydrogen energy studies. Final Report. US: NREL; 1993. DOE Contract n°-XR-2-11265-1